Global Change and Local Places

Estimating, Understanding, and Reducing Greenhouse Gases

BY

Association of American Geographers Global Change
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Contents

1

A grand query: how scale matters in global change research

Robert W. Kates and Thomas J. Wilbanks

Grand queries are fundamental questions that transcend the form and substance of individual sciences; they often appear simultaneously in many disciplines. A recurring grand query focuses on scale: how to relate universals to particulars, wholes to parts, macroprocesses to micro-behavior, and global to local. Biologists ponder the linkages among molecules, cells, and organisms; ecologists among patches, ecosystems, and biomes; economists among firms, industries, and economies; and geographers among places, regions, and Earth (Rediscovering Geography Committee 1997: 95–102; Alexander *et al.* 1987; Holling 1992; Levin 1992; Meyer and Turner 1998; Meyer *et al.* 1992; Turner, M. G. *et al.* 1993). Scientists in many disciplines worry about non-linear processes and complexity: whether understanding its components can explain the properties of a large system (Gallagher and Appenzeller 1999). Or the reverse, as in the case of global climate change: can the rapidly accruing understanding of the large Earth system inform the ways people and biota in particular places alter climate and in turn are affected by climate change?

This chapter places the Global Change and Local Places project in the context of a grand query: how *scale* matters in global climate change. It examines the scale at which global change and responses to it take place, and how well the current scales of science and policy match the current scales at which changes are engendered. This analysis is rooted in a simple causal chain of human-induced climate change and a brief summary of the current state of scientific knowledge for each link in that chain. The analysis draws heavily upon the third assessment report of the Intergovernmental Panel on Climate Change (Houghton *et al.* 2001; McCarthy *et al.* 2001; Davidson *et al.* 2001).

The causal chain consists of six links: (1) driving forces, (2) human activities, (3) radiative forcing, (4) climate change, (5) impacts, and (6) responses. The Global Change and Local Places team examined the geographic scale of each link and asked how well current scales of assessment – observation, research, and policy – match the scales of each of the six processes. For some links, serious scale mismatches exist between processes and assessments, mismatches that the global change research community increasingly recognizes. The problems such scale disjunctures cause can be addressed both by moving current approaches downscale and by employing the bottom-up approach taken in the Global Change and Local Places project and in similar studies of global change.

How scale matters

Wilbanks and Kates (1999) have suggested two sets of arguments as to how scale affects global climate change. The first set concerns the way the world works. Human-induced climate change arises from interactions between the different domains of nature and society, each composed of many systems operating at different scales in space and through time, resulting in mismatches in scale between causes and consequences. For example, many social scientists seek to understand relationships between *agency* (intentional human action) and *structure* (institutions and other regularized relationships within which human action takes place). The scale of agency is almost always more localized than that of structure.[1] When global structure and local agency interact across different domains, on different time scales and over different areas, the resulting relationships are neither easily understood nor readily predictable.[2]

The second set of arguments is rooted in the practice of science. Current ways of relating global climate change to localities are top-down: from the global toward the local. They begin with climate change scenarios derived from global models, even though those models have little regional or local specificity. But at global scales, understanding the complex interactions among the environmental, economic, and social processes that drive change often seems intractable (Cox 1997).[3] Place-based research, well-grounded in local experience, offers a more tractable alternative for tracing these complex relationships. Though locality studies may be more tractable, however, they are also less generalizable. Where possible therefore, case studies should constitute natural experiments carefully chosen for comparability and investigated by using a common study protocol.[4]

Small study areas offer variety as well as tractability. The variance from a sample of small geographic areas will likely be greater than the variance from a sample of large areas (Figure 1.1). The greater variety in processes and relationships at local scale represents an opportunity for learning about causes and consequences of global climate change that

[1] For example, consider the range of human responses to natural and technological hazards. Most major decisions are made locally (Cutter 1993), but within larger structures that *mandate* some actions by law, regulation or court order, *encourage* some actions through persuasion or incentives, and *inform* those creating risk (who may voluntarily reduce it) and those suffering risk, who may learn to tolerate the hazard (Kasperson *et al*. 1985; Palm 1990; Cutter 1993; Hewitt 1997). Other literature reinforces this impression, considering evidence about the scale of human-ecological self-determination (Wilbanks 1994) and scale and consensual decision-making regarding the use of technology (Wilbanks 1984; Aronson and Stern 1984; Chapter 7).

[2] Modelers such as Holling (1995: 27) identified a few cases of managed ecosystems (boreal forests, boreal prairies, and pelagic systems) where the relevant scales of sizes and speeds and their interactions are well understood. But in regions where human activities predominate, interactions are more complex; a study of nine 'regions at risk' where large subnational zones are undergoing great environmental stress found interactions to be highly diverse and complex (Kasperson *et al*. 1995).

[3] Root and Schneider (1995) suggest *strategic cyclical scaling* for analyzing interactions among processes operating at different climatic and ecological scales. Strategic cyclical scaling would involve continuing cycling of studies between large-scale associations that suggest small-scale investigations in order to test the causes and driving forces of the large-scale patterns.

[4] For examples, see the case studies of natural hazards by White (1974), population density and agriculture in Africa by Turner, B. L. *et al*. (1993), and poverty and environment by Kates and Haarmann (1992).

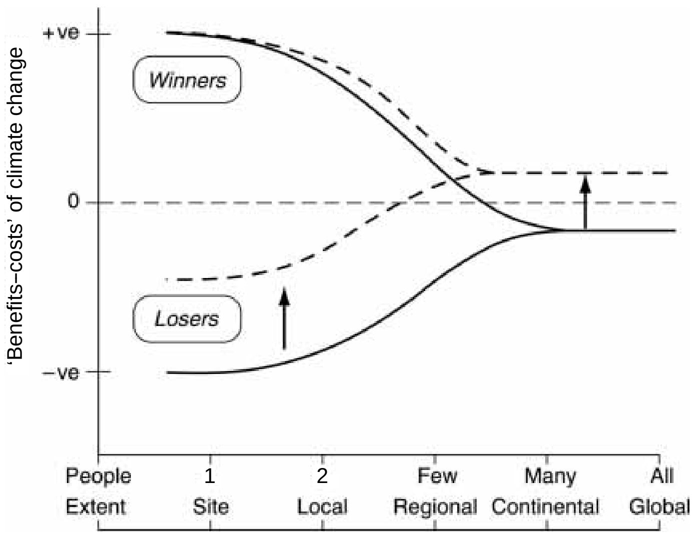

Figure 1.1 Scale-dependent distribution of impacts of climate change (adapted from Environment Canada).

often are obscured when behavior is averaged over larger areas.[5] Finally, in many situations researchers looking at an issue from a global perspective come to conclusions different from those reached by investigators looking at that same issue from a local perspective.[6] Focusing exclusively at a specific scale can lead to conclusions that are highly dependent on the information collected, the parties seen as influential, and the processes that operate at that scale; information, actors, and processes that operate at other scales may be overlooked.[7]

Climate change: causes and consequences

Central to scale considerations in climate change is the global greenhouse effect whereby natural and human-induced greenhouse gas emissions affect radiative forcing of the climate. Solar radiation is the essential source of life on Earth, providing heat and light and powering the movements of air and water that humans experience as climate. Life on Earth has

[5] For example, persistent decadal fluctuations of greater than average temperature (up to 1 °C annually or 2 °C seasonally) and precipitation (approximately 10% annually) have occurred in most areas of the United States during the period of modern records. These natural variations that mimic what might occur as a result of global warming have been identified for all climate divisions of the United States (Karl and Riebsame 1984). In one study, such fluctuations were used to study the impacts of possible global warming on the runoff portion of the hydrologic cycle (Karl and Riebsame 1989).

[6] For example, macro-scale analysis of climate change impacts on agriculture finds little net loss in productivity; one region's gains offset another region's losses, especially with carbon dioxide fertilization and modest levels of adaptation (Fischer *et al.* 1994). Micro-level studies identify developing country smallholder agriculturists, pastoralists, wage laborers, the urban poor, refugees, and other destitute groups as especially vulnerable (Bohle *et al.* 1994).

[7] For instance, Openshaw and Taylor (1979) have demonstrated that simply changing the scale at which data are gathered can change the correlation between variables virtually from +1 to −1.

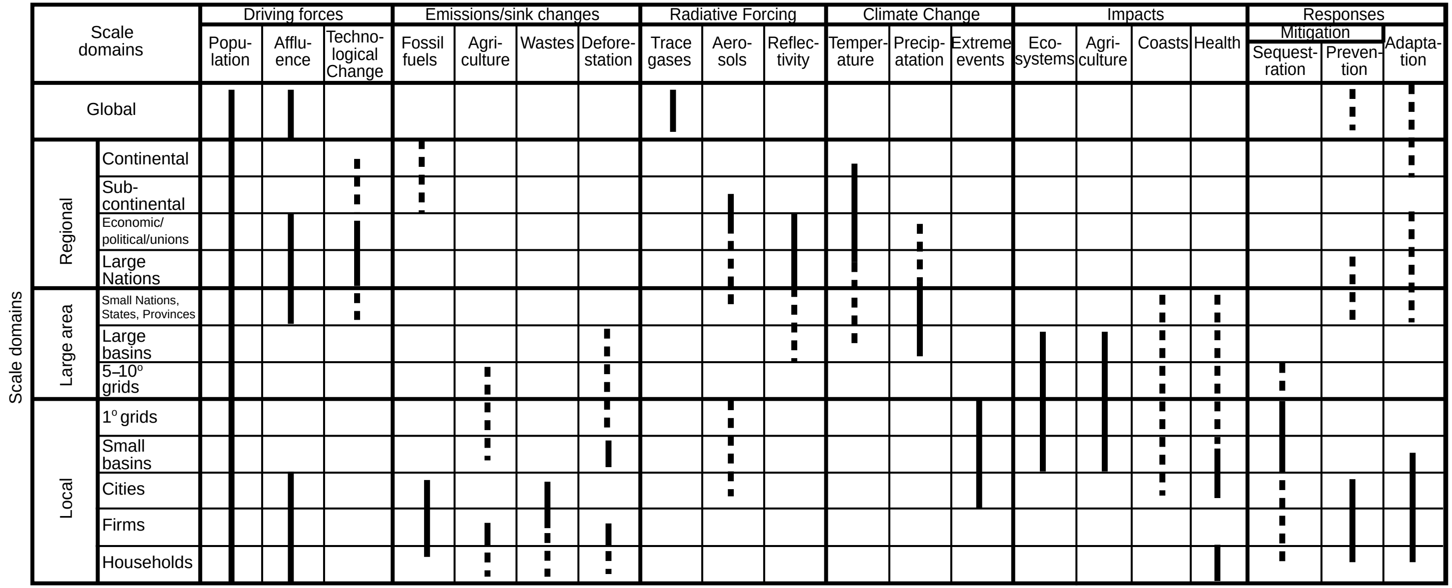

Figure 1.2 Scale domains of climate change and consequences. Depicts the scale of actions, not necessarily the locus of decision-making. Dashed lines indicate occasional consequences or a lower level of confidence.

evolved beneath a greenhouse-like atmosphere. Short-wave solar radiation passes through the atmosphere and is absorbed by the Earth's surface, which it warms. The Earth then radiates energy to space as long-wave infrared radiation. Minor gases in the atmosphere (water vapor, carbon dioxide, ozone, methane, and nitrous oxide) that are transparent to incoming solar radiation absorb and re-emit some of the outgoing long-wave radiation to again warm the Earth's surface and its lower atmosphere. This natural greenhouse effect warms the Earth by as much as 33 °C (91 °F), thus making much of life on Earth possible. Human actions have altered and are continuing to alter natural biogeochemical cycles in ways that increase the concentration of trace gases in the atmosphere.

Viewing the Earth's greenhouse effect and its consequences as a causal chain (Figure 1.2) highlights six major links:

- the societal *driving forces* of
- *human activities* that produce greenhouse gas emissions. Greenhouse gas emissions then provide
- the enhanced *radiative forcing* that
- induces *climate change*, which
- *impacts* nature and society. Finally, the anticipation and experience of the effects of climate change encourage
- a range of *human responses* to prevent climate change, mitigate it, or adapt to it.[8]

Since the onset of the industrial revolution, *human activities* that generate greenhouse gases have increased the concentration of those gases in the atmosphere. According to the third assessment report of the Intergovernmental Panel on Climate Change (Houghton *et al*. 2001) methane has increased by 145%, carbon dioxide by 31%, and nitrous oxide by 16%. In addition, new gases not found in nature (primarily halocarbons, that is carbon compounds containing bromine, chlorine, fluorine, or iodine) have been released into the atmosphere. Current estimates of enhanced *radiative forcing*[9] from these greenhouse gases since pre-industrial times are $+2.425\ \mathrm{W\,m^{-2}}$. Carbon dioxide accounts for 60% of this enhanced forcing, methane for 20%, nitrous oxide for 6%, and halocarbons for 14%. Fossil fuel extraction and combustion releases the largest quantity of greenhouse gases, followed in order of importance by deforestation and other land cover changes, agriculture (including cattle rearing, rice production, and fertilizer production and use), industrial production, waste disposal, and refrigeration and air conditioning. Particulates from fossil

[8] This chain is shown as a linear sequence for simplification. It consists, of course, of a complex set of relationships with feedbacks at every link affecting other links. More elaborate and operative models of all or most of these links are found in integrated assessments that are designed to inform various stakeholders of alternative courses of human action related to climate change and their associated costs and benefits (Parson and Fisher-Vanden 1997). At least 15 major integrated assessments are underway worldwide. While they differ markedly, systematic comparisons of their inputs and outputs have begun (Toth 1995). A common characteristic of these models is their large scale: two thirds of them, in fact, are global- or continental-scale models (Morgan and Dowlatabadi 1996).

[9] Radiative forcing is a measure of the effect (in watts per square meter) a factor has in altering the balance of incoming and outgoing energy in the Earth–atmosphere system. A positive forcing warms the surface and a negative forcing leads to cooling.

fuel combustion and biomass burning, particularly sulfate aerosols, reflect incoming solar radiation and lead to cooling that offsets positive radiative forcing. Ozone depletion in the stratosphere caused by halocarbons also reduces radiation forcing, while ozone increases in the lower atmosphere (troposphere), mainly from fossil fuels, augment forcing.

The human activities responsible for these greenhouse gas changes are driven by *forces* that have been widely generalized as the **I** = **PAT** identity (Ehrlich and Holdren 1972), in which changes in **I**mpacts (emissions in this case) are a function of **P**opulation, **A**ffluence, and **T**echnology that increases or decreases impacts or emissions per capita.[10] These *driving forces*, population, affluence, and technology, are again intermediate to more basic driving forces: the complex array of interdependent cultural, economic, environmental, and social contexts examined in Chapter 9 of this volume. Globally, a study using country data for 1989 as observations found average emissions to be driven almost equally by population and affluence (measured by per capita gross domestic product). The effect of population increases with size, however, while the effect of affluence decreases in the richest countries (Dietz and Rosa 1997).

According to the Third Assessment Report (Houghton *et al.* 2001), the indicators of *climate change* over the past century include:

- an increase in global mean surface temperature of 0.4–0.8 °C (0.7–1.4 °F) since about 1860;
- the twentieth century is likely to have been the warmest century in a thousand years in the Northern Hemisphere, with the 1990s the warmest decade, and 1998 the warmest year;
- nighttime temperatures have increased twice as fast as daytime temperatures and the frost-free season has increased in many mid- and high-latitude regions;
- decreases in Northern Hemisphere snow cover (10% since the late 1960s), Arctic Sea ice (10–15% since the 1950s), and alpine glaciers (almost everywhere), but no trends evident in Antarctic sea ice;
- sea level has risen 10–20 cm (4–8 in) since 1900, and this rate of increase is about ten times larger than the average rate of the past 3000 years;
- precipitation has increased by 0.5–1.0% per decade in the twentieth century over most of the mid- and high-latitude Northern Hemisphere, with an increase in heavy and extreme precipitation events and possible flooding, but no increase is evident in hurricanes or severe cyclonic storms;
- warm *El Niño* events have been more frequent, intense, and persistent since the 1970s; and
- all of these climate changes have already impacted avian, insect, plant, and animal life in aquatic, terrestrial, and marine environments on all continents.

[10] While there has been widespread use of the I = PAT identity at a global scale, when one moves down scale even to large regions, the complexity and richness of explanation increases. For example, in a study of nine environmental zones under great environmental stress (Kasperson *et al.* 1995), the range of explanatory variables expands beyond population, affluence and technology to include the economic, social, and political institutions that govern resource and environmental use, along with belief systems and attitudes. Poverty emerges as the obverse of affluence and a major driving force in its own right.

These and other indicators, particularly the similarity between observed climate changes and simulated climate from model runs over the past thousand years that included human-induced driving forces as well as natural forces (solar output and volcanic eruptions), led the Intergovernmental Panel on Climate Change's Third Assessment to conclude that 'increasing concentrations of anthropogenic greenhouse gases have contributed substantially to the observed warming over the last fifty years.' Moreover, global average temperature will rise from 1990 to 2100 by about 1.5–6.0 °C (2.7–10.8 °F), and a sea level rise of 14–80 cm (5.5–31.5 in) is possible under a range of emission scenarios. Precipitation will continue to increase, especially over northern mid- and high latitudes, and will increase in some low-latitude regions and decrease in others. Many types of extreme events will also increase, as will continued melting of snow and ice. The potential for large-scale and abrupt changes has been identified through such mechanisms as slowing of the ocean circulation that transports warm water to the North Atlantic, disintegration of the west Antarctic ice sheet, and releases of terrestrial carbon or methylhydrates from permafrost regions or coastal sediments (McCarthy *et al*. 2001).

Projecting these and similar changes into the future, the Intergovernmental Panel on Climate Change's Third Assessment finds many ways in which natural and human systems become more vulnerable, including:

- as climate changes, ecosystems or biomes are not likely to move as a whole; instead species composition and dominance will change, yielding ecosystems markedly different from ones seen today. In particular, endangered species, arid and semi-arid areas, wetlands overlying permafrost, boreal forests, and coastal and marine ecosystems – especially coral reefs, salt marshes and mangrove forests – appear most vulnerable;
- sea-level rise will increase the vulnerability of some coastal populations to flooding and erosional land loss, especially in deltaic regions and small island states;
- climate change may adversely affect human health due to heat waves and increases in the transmission of such vector-borne infectious diseases as malaria, dengue fever, leishmaniansis, mosquito-borne encephalitis, and cholera and diarrheal disease, because of increases in the active ranges and seasons of their vectors;
- on the whole, global agricultural production could be maintained in the face of climate change but not in the subtropical and tropical areas that are home to many of the world's poorest people. There, changes in climate extremes can lead to major increases in vulnerability through increases in such natural hazards as heat waves, drought, flooding, storm surges, coastal erosion, and possibly cyclones, while in a few regions, vulnerability will be moderated by decreases in cold waves and frost days (McCarthy *et al*. 2001).

As climate changes or is expected to change, many human-initiated *responses* may follow that are intended to prevent or mitigate the consequences of climate change, or to adapt to climate changes that cannot be prevented or mitigated. Mitigation efforts will focus on human intervention to reduce emissions or on enhancing the action of greenhouse gas sinks, usually by augmenting carbon uptake in forests, soil, and perhaps the oceans. Over the next century the world's energy systems will be replaced twice over, and major reductions in emissions could come from shifting from high-carbon coal to low-carbon oil, lower-carbon gas, and no-carbon nuclear power, or to no-net-carbon wood and plant materials and the no-carbon renewable sources: sun, wind, and water. The efficiency of converting fossil fuel to electricity could double to 60% from its current 30%. Ten to twenty percent of carbon emissions cumulating between now and 2050 could be prevented or stored in such land covers as forests, rangelands, and crop lands. In the short run, combinations of technologies have the potential of reducing global greenhouse gas emissions close to or even below those of the year 2000 by 2010 and even lower by 2020. In the long run, a combination of known technological options and needed socioeconomic and institutional changes can achieve stabilization of the Earth's atmosphere in the range of 450–550 parts per million (ppm) of carbon by volume, a doubling of pre-industrial greenhouse gases. Even if this is achievable, significant adaptation will be required to cope with the impacts already observed and with the many additional changes in physical, biological and human systems that will take place over this century.

Scale in climate change: action and assessment

Worldwide climate change is but one of many environmental changes that are part of the remarkable global changes underway in population, health and well-being, urbanization, economies, technologies, cultures, politics, and institutions (National Research Council 1999). Two major pathways transform regional environmental problems into global problems (Turner *et al*. 1990). *Cumulative* global environmental change begins with common but widespread local problems such as groundwater depletion, pollution, or species extinction. When localized change accumulates to a significant fraction of the total global area or resource, cumulative global change results. *Systematic* global changes are direct alterations in the functioning of a global system exemplified by the effects of greenhouse gas emissions on global climates or the ways ozone-depleting gases affect the stratosphere. Addressing the major systemic changes in global climates and their causes and consequences within domains of nature and society, Clark (1985, 1987) characterized the domains of climate, ecology, and society in terms of their geographic and temporal scales of operation (Figure 1.3). The basic mismatch of scales in space and time at which essential elements of global climate change operate is striking (Wilbanks 2002).

Using the Global Change and Local Places causal structure as a template (Figure 1.2), scale in climate change and its consequences vary more than a billion-fold, from the areal extent of a household, farm, or factory, to the Earth as a whole. Each of the causal links in the chain of driving forces and human responses operates at a characteristic scale within which most actions inside that domain occur. As currently practiced, climate change assessment also uses characteristic scales for each domain, and the relationships between the scales of observation, research, and policy, and the scales of major activities in each link in the causal chain, are critical. The scale at which most action related to each of the domains takes place may well differ from the scale at which decision-making for these actions occurs. As noted above, the scale of action is often smaller than that of the structural context within which action takes place (Figure 1.2).

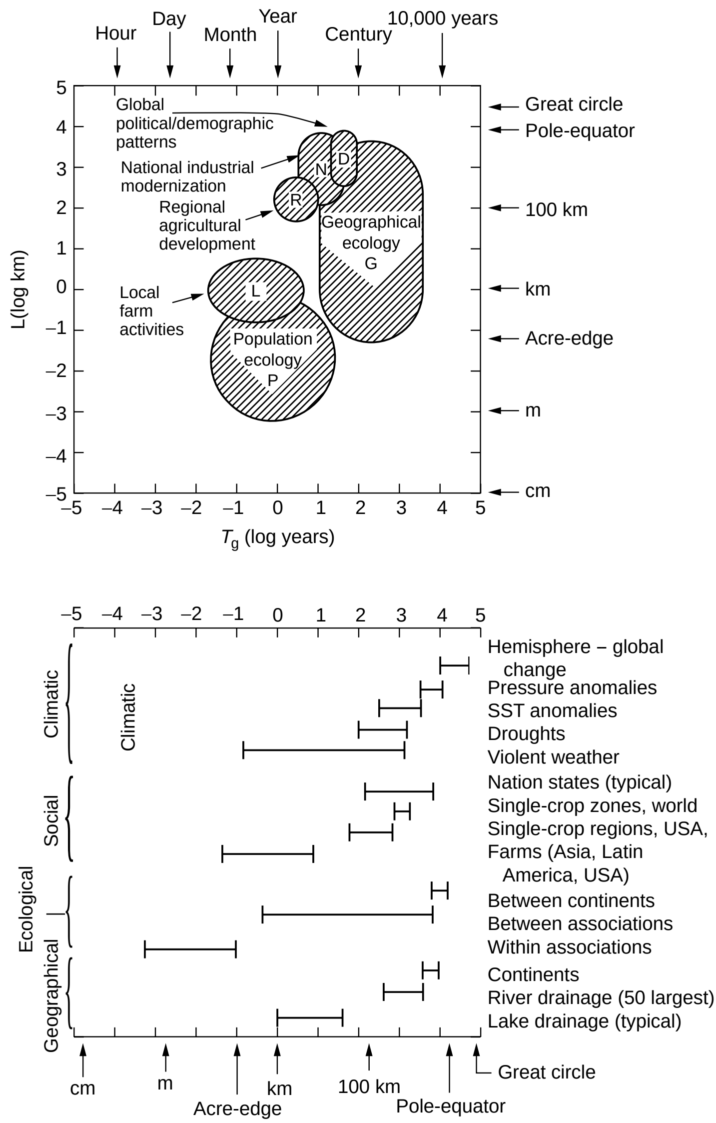

Figure 1.3 Geographic and temporal scale domains (from Clark 1985).

The Global Change and Local Places project examined the scales of action and assessment at four levels: global; regional (continental, subcontinental, economic and political unions, and large nations); large area (small nations, states, provinces, large river basins, and the 5–10° grids commonly used in global climate models); and local (1° grid squares, small river basins, cities, households, farms, firms, and factories). Considerable overlap occurs in such a qualitative scale classification, of course, but it does broadly distinguish differences in scale by size and by common geographic and social units.

Driving forces

The driving forces of population, affluence, and technology (Chapter 9) are intermediate, driven in turn by interdependent cultural, economic, environmental, and social imperatives. Population serves as a driving force because people and households require energy and materials to subsist, some of which release greenhouse gases when produced and used. While the amounts differ greatly among societies, each additional person or household requires some increment of resources and emits a modest amount of carbon dioxide. Affluence drives climate change insofar as it expands demand for energy and materials that release greenhouse gases. Technology is a driving force insofar as different energy and materials production and consumption technologies release markedly different kinds and quantities of greenhouse gases.

Almost all population-creating activity is highly localized in households or their equivalents. Much of the production and consumption enabled by affluence takes place in households, farms, and factories, whereas the technologies most related to climate change operate over larger (but far from universal) areas. Even such global features as automobiles or electricity generation embrace an enormous range of energy and emission efficiencies over large areas and small regions. Within Europe, for example, France emits only half the per capita carbon dioxide that Germany does because of its widespread use of nuclear power. Automobiles in the United States sold in 1995 averaged 8.6 km l^{-1} (20.4 mpg) (United States Environmental Protection Agency 2002), compared with 13.6 km l^{-1} (31.9 mpg) in Europe in the same year (Perkins 1998).

Population numbers and growth are enumerated locally and aggregated to larger areas, from birth registries in industrialized countries, survey data in developing countries, or by censuses everywhere. The populations of almost all localities are known within 20% and in countries with modern statistical services within 3% – better estimates than exist for any other living things and for most other environmental concerns. As a driving force, population can be projected reliably over the short and long term as well as or better than any other aspect of human behavior. Much is also known about the number of children people want and their reasons for having or not having them. Detailed health and demographic surveys of representative national samples have been taken in 27 developing countries. In the policy realm, clear and reliable prescriptions for slowing population growth have been formulated.

Affluence (gross domestic product in the aggregate or disposable income for households) is relatively well measured, but the links between income and the demand for energy and materials that emit greenhouse gases vary greatly among societies and technologies. Much is known at global scale about energy transformations, due in part to common units for conversion among different technologies (Nakicenovic *et al.* 1998). Detailed estimates of energy use are available for countries, regionally, and for the entire world. The forces that drive energy use have been decomposed for industrialized countries and those parsings also highlight the substantial differences in available energy technologies among places (Schipper and Meyers 1992; Schipper *et al*. 1997).

For materials, aggregate data in common units do not exist on a global basis, except for some specific items including materials for energy production, construction, industrial minerals and metals, agricultural crops, and water (World Resources Institute *et al.* 1998). Calculations of material use by volume, mass, or value yield different trends. For limited classes of materials (for example, forest products in the United States), studies of major changes in technological efficiency over time are available (Wernick *et al.* 1997). Overall, the driving force of population is best observed and understood at all scales, whereas the relationship between income and the demand for goods produced by energy and material technologies that emit greenhouse gases is only partly understood, and is generally observed only for large areas.

Emissions and land cover change

To meet population needs and the demands of affluence, people undertake production and consumption that emit greenhouse gases. The greenhouse gases carbon dioxide, methane, and nitrous oxide are released mainly in fossil fuel production and use (manufacturing, electricity generation, transportation, and household heating), forestry and agriculture (land clearing, timber production, wetlands, livestock raising, and fertilizer application), and waste disposal (landfills and incineration). In addition, ozone-depleting chemicals are manufactured and used in a variety of industries, household appliances, and vehicles. Much fossil fuel combustion also emits airborne particles (mainly sulfate aerosols) that act regionally to counter greenhouse warming. All this takes place at the most local of scales: in power plants, factories, vehicles, buildings, households, fields, forests, and animals that constitute billions of point or small area sources of emissions, aerosols, and instances of land cover change.

Analysts usually estimate greenhouse gas emissions by tracking a process that emits the gases, converting the process measure to greenhouse gas releases, and then normalizing the different gases to greenhouse warming potential, or carbon dioxide equivalents. A well-established procedure for such estimates has been developed under the aegis of the Intergovernmental Panel on Climate Change (1992) to meet national reporting requirements of the Framework Convention on Climate Change. Thus estimates of carbon dioxide emissions from fossil fuel consumption and cement production are now available for all countries. The estimates have been extended to smaller areas in some countries, notably by the United States Environmental Protection Agency (1995), in order to calculate state emissions, which now are available for 35 of the 50 United States. Carbon dioxide emissions estimates, though made at local scales, are not true estimates of emissions. The two available sets of $1^\circ \times 1^\circ$ carbon dioxide emissions data for the entire world are national estimates allocated to each 1° grid cell in proportion to the estimated share of total population residing within that cell (Andres *et al.* 1996; Olivier *et al.* 1997). Large area and many point source aerosol estimates, particularly for sulfates, are available for most industrialized countries (Graedel *et al*. 1995). Land cover data are more localized, some at the scale of a square kilometer based on satellite observations (http://atlas.esrin.esa.it:8000/) or at even finer scales such as 30 m resolution imagery for the coast of the United States (Dobson *et al.* 1995).

At the global level, past trends in carbon dioxide concentrations in the atmosphere have been estimated for hundreds of millennia, carbon dioxide emissions have been estimated for the 250 years since 1750, regional aerosol data have been calculated in industrialized countries for half a century, and satellite estimates have been made of land cover change over most of the world for the period since 1980. Forecasts of future emissions are available in Intergovernmental Panel on Climate Change reference scenarios for the globe and for major regions based largely on the I = PAT driving force variables: population, economic growth, and technological change. Regional air pollution models for North America, for Europe, and most recently for Asia, provide similar data for future aerosol distributions (McDonald 1999; Tuinstra *et al.* 1999). A major research project aspires to build similar models for land cover change (Turner *et al.* 1995).

Overall, a gross mismatch exists between the billions of point and small area sources of emissions on the one hand, and on the other hand the aggregated data on greenhouse gas and aerosol emissions for nations, regions, and the world, and the assessments and policy analyses that have been based upon those coarse data. Only land cover data are effectively localized, but little is understood about land cover change resulting from deforestation, agriculture, grazing, and urbanization and the resulting emissions of greenhouse gases.

Radiative forcing

While such trace gases as carbon dioxide, methane, nitrous oxide, and ozone-depleting chemicals originate from local sources and are estimated at national and regional scales, they diffuse rapidly in the atmosphere. Consequently, they can be measured globally. Carbon dioxide has been observed in the atmosphere since 1958 and other trace gases (methane, nitrous oxide, and ozone-depleting chemicals) since 1978. Sulfate aerosols arise over large areas, are concentrated in urban and industrial regions, and are transported regionally; they therefore act regionally to counter greenhouse warming potential. Greenhouse gases generated by local changes in land use also diffuse into the atmosphere rapidly, and changes in the albedo (reflectivity) of the earth's surface must be extensive over large areas to significantly affect global climate. The extent of Arctic and Antarctic sea ice may affect albedo.

Much remains to be learned about the distribution of some gases and aerosols in the atmosphere, but current observations can be fed into climate models to estimate the enhanced radiative forcing of the climate system that results from human-induced emissions. Overall, the fit is good between the scale of radiative forcing in the atmosphere, what is observed and what needs to be known for scientific understanding of the atmosphere, and for policy formulation and evaluation with respect to the atmosphere.

Climate change

The three features of greatest interest in climate change are temperature, precipitation, and extreme weather events. For each of the three, many characteristics of interest exist: temperature changes in the stratosphere, troposphere, land surface, and oceans; in land and sea; in the Northern and Southern Hemispheres; at low and high latitudes; between day and night; and between winter and summer, among others. Each of these dimensions changes in response to radiative forcing in different directions or at different rates and scales, and the patterns of such changes might be the best confirmation of human-induced climate change.

Clark (1985) sought to compare some of the spatial domains of climate events and found (Figure 1.3) that temperature change as evidenced by historic warming trends appears in areas greater than 10,000 square kilometers (3,850 square miles), precipitation or its absence (as in major droughts) takes place in areas of 1,000 – 10,000 square kilometers (385 – 3,850 square miles), and extreme weather occurs at a scale of 0.1 – 1,000 square kilometers (0.04 – 385 square miles). Overall, the characteristic scales at which climate change occurs vary a million-fold.

The match between the active domains of climate events and the scales at which major parameters of climate are observed, aggregated, and modeled, also varies greatly. The best fit exists for currently observed climate events, given a dense web of observing stations on land, an increasing number at sea, and the availability of satellite observations since 1979.[11] These data can be aggregated into relatively homogenous large areas such as the 344 climatic divisions of the mainland United States, which match well the scales of temperature and precipitation change. The 140 year instrument record has now been placed in a context of millennial length by such proxy variables as tree rings and corals, and in a frame extending back hundreds of thousands of years by gases trapped in ice caps (Crowley 2000).

But crucial projections of future climates caused by radiative forcing from enhanced emissions depend solely on complex models of the Earth's climate. The current resolution of these models (5° grids at best) are thought to be reliable primarily for temperature, and only over large latitudinal bands or continental zones. Overall, climate itself is measured as well as or better than any of the causal facets of climate change, and those measures can be aggregated to match the scale of climate events. Yet there remains a large gap between climate change forecasting models and the scales at which extreme weather and long-term climate are experienced.

Impacts

Changes in temperature and precipitation and extreme weather profoundly affect natural and managed ecosystems and human activities and well-being. The Intergovernmental Panel on Climate Change assessment (McCarthy *et al.* 2001) focused on the vulnerability of seven natural and human systems that include the major terrestrial and marine ecosystems and that provide water, food and fiber, human infrastructure, and health, as well as on eight continental and larger-sized regions. Climate helps define the areal extent of many of these impacted systems, and effects of climate change impacts may appear first as changes at the margins of ecosystems, crop regions, shorelines, or disease vector habitats. The scale

[11] Many areas of the world remain only sparsely monitored, many records need to be revised for reliability and to remove site changes and urban effects, and much needs to be learned about relationships between satellite and ground observations (National Research Council, Panel on Reconciling Temperature Observations 2000).

of these climate-bounded areas varies considerably, but tends to approximate large areas or their borders. Large ecosystems in the United States, for example, may vary within the same size range as the 50 states. In one classification, the 52 ecoregions of the United States range from the 9,600 square kilometers (3,700 square miles) of the Black Hills of South Dakota, to the 751,000 square kilometers (290,000 square miles) of the Great Plains – Palouse Dry Steppe region (Bailey 1995). Major agricultural crop regions approximate the largest of the 52 ecoregions, encompassing three to eight states in areal extent (United States Department of Agriculture 1987). Coastal zones are very different sized regions. The narrow but continuous slivers of land subject to a 1 m rise in sea level range from several square kilometers on small islands, through thousands of square kilometers for medium-sized countries, to tens of thousands of square kilometers in low-lying areas in Bangladesh, China, and the United States. Climate changes will also alter the habitats of insect and animal vectors of human and biotic diseases. Such changes might take the form of increased bands of malarial infestation or narrowed zones of river-constrained onchocerciasis. Similarly, changed or intensified tracks of such extreme weather events as hurricanes, tornadoes, hail, and wind would also vary from localities to regions.

Most climate change impact analyses to date begin with outputs from global climate models or with a hypothesized arbitrary change in temperature, precipitation, or sea level. Then, using models or analogs, impact analysts try to assess positive and negative impacts on natural ecosystems and human activities. Because of the coarse resolution and poor reliability of climate models for large areas, impact analysis (especially Intergovernmental Panel on Climate Change assessments) have focused on major ecosystem types, generic economic sectors, or very large regions – usually at continental or subcontinental scales. Agricultural impact studies have been made for major crop types and ecosystems, and for large biomes. A notable exception has been studies of sea level rise, which can be highly locality-specific, though sometimes complicated by local uplift and subsidence. In general, impacts that occur at local or regional scales are poorly matched by generic assessments, which are rarely locality-specific.

Responses

People and societies will in time come to anticipate climate changes and their consequences and will seek to prevent change, mitigate its extent, or adapt to and reduce their vulnerability to such changes. Preventive actions to remove greenhouse gases from the atmosphere or to change the Earth's radiation balance are often called *geoengineering*. Actions to remove carbon by collecting it in the course of energy production and sequestering it in the ground or the deep oceans have shown substantial progress and at least one current application in Norway (Parson and Keith 1998). The most feasible immediate prevention strategy appears to be the removal of carbon from the atmosphere by increasing carbon storage in forests, soil, and perhaps the oceans. To be effective in preventing or ameliorating climate change, storage must be enhanced over large areas. Yet the actions that must be taken to accomplish enhanced storage – tree planting, reversion of fields to forests, and stimulation of photosynthesis – must be accomplished locally even if they eventually cumulate to large areas.

Reducing greenhouse gas emissions, a major focus of mitigation, also requires action at the billions of point sources where emissions occur. Creating structures that encourage such local actions requires international agreements, national policies, corporate decisions, and public support: efforts that span all scales from local to global. Adaptation, even more than abatement, takes place locally, but similarly can be encouraged by global, national, and corporate policies and by public attitudes. Human responses to climate change will depend on a combination of local decision and actions and state, national, and global mandates and enabling policies.

To date, most mitigation studies have been conducted for rather large areas. Research on carbon storage or enrichment in forests or fields is highly localized, but studies of storage potential are usually based on large-area ecosystems and land uses. Greenhouse gas abatement studies are usually generic rather than place-specific, organized by technological or economic sectors. Thus volume three of the third Intergovernmental Panel on Climate Change report (Davidson *et al.* 2001) has chapters that address mitigation generically in buildings, transport, industry, agriculture, waste management, and energy supply. Similarly, the second volume of the Intergovernmental Panel on Climate Change report (McCarthy *et al.* 2001), which addresses impacts, adaptation, and vulnerability, considers adaptation for each of the seven systems and eight regions it addresses, but with rare exceptions, only in the most generic ways. Thus the mismatch between the highly localized scale of human responses on the one hand, and generic assessments of the range of human mitigation and adaptation options on the other, remains serious.

To sum across the links in Figure 1.2, an envelope of the larger-scale actions (global and regional) appears as a wave in which global and large regional actions characterize the driving forces of population, affluence, and technological change, the radiative forcing of gases, aerosols, and reflectivity, climate change, and preventive and adaptive responses. In contrast, emissions and sinks and the major impacts of climate change are far more localized.

Addressing the mismatch in scale domains

Thus for emissions impacts and most responses, there is a grave mismatch between the scale domains of human activity on the one hand, and of observation, research, and policy assessment and formulation on the other. This gap between the knowledge that is needed to act locally and what is currently being done globally to generate knowledge about climate change and its impacts is increasingly recognized as an impediment to further progress. Efforts are therefore underway to move *down* scale in each of the causal domains.

Downscaling top-down approaches

Driving forces

Decomposition analysis identifies the differing importance of the various driving forces of greenhouse gas emissions. It has been applied to the forces driving eighteen years of carbon dioxide production in ten countries, and has been used to identify major differences in sources and in emissions even among highly industrialized countries (Schipper and Myers 1992; Schipper *et al*. 1997). At a larger regional scale than countries, six driving forces (population growth, economic growth, energy intensity, technological change, resource base, and environment) are used as determinants of future energy systems for 11 world regions (Nakicenovic *et al.* 1998).

Emissions and land cover change

Efforts are underway to complete the estimation of greenhouse gas emissions using standardized Intergovernmental Panel on Climate Change methodology for all nations in order to downscale these estimates to regions and large areas (Graedel *et al*. 1993, 1995). Estimates are now available for all countries based on population figures when direct data are lacking (Carbon Dioxide Information and Analysis Center 2002). In 56 developing and transitional countries, studies are underway intended to create national capacities for assessment and to identify selected regional or sectoral impacts of climate change, in addition to estimating greenhouse gas emissions (Dixon *et al*. 1996; United States Country Studies Program 2002). In the United States, the Environmental Protection Agency has downscaled the Intergovernmental Panel on Climate Change emissions methodology, making appropriate modifications for calculating state (large-area) emissions, which have been completed or are underway in 35 states (United States Environmental Protection Agency 1999). Similar steps have been taken in Australia (Australian Greenhouse Office undated). Gradually, downscaling has moved farther down, particularly to city and metropolitan areas (McEvoy *et al.* 1997). There is increasing interest and action on the part of corporations to inventory their own emissions, to register or publicly disseminate changes in their emissions, and in some cases to create intercorporate trading in emissions regimes (Loreti *et al.* 2000). A quarter of the increase in carbon dioxide emissions over the past 20 years is attributed to land use change, and satellite imagery has provided continuous coverage of the earth since 1992 with the potential to measure changes in land cover and use for areas as small as one square kilometer, or 0.39 square miles (Global 1KM AVHRR Server 2002).

Climate change

A major effort is underway to downscale global climate change models to yield more credible forecasts of large-area climate changes and impacts via two major approaches. The *nested* approach employs large-area regional models (Girogi *et al*. 1994; Jenkins and Barron 1996) that simulate regional topography, vegetation, and water bodies nested within larger global models. Alternatively, *statistical* relationships can be used to link the major features of global models with more local aspects of climate or weather. The recent United States national assessment of climate change used two different models to downscale climate changes for 19 different regions of the country (National Assessment Synthesis Team 2000). Some models in the United States currently forecast at a scale of a 50 km grid, while experiments are being undertaken in Japan with a 10 km grid.

More global change researchers are now focusing on short-term climate forecasting, moving from the decades-to-centuries perspective of greenhouse warming to seasonal and interannual forecasts, whose reliability for certain areas has improved considerably. Recent El Niño forecasts anticipated the 1997–8 ocean warming by as much as six months, although they performed less well later into the event (Kerr 2000). Such forecasts are more relevant locally and regionally, and when reliable, build user confidence in undertaking anticipatory responses and adaptation to climate change.

Impacts

Efforts to identify place-specific impacts of global climate change are increasing (Rosenzweig and Hillel 1998). Using climate model results to create a regional or large area scenario has traditionally combined model outputs that vary widely from model to model and provide a range of potential regional climate changes on which to base impact assessments. More promising are the major efforts underway to downscale climate model outputs noted above. Another option is to use analogs from the past (historic climate events) or from other places (climate-bounded ecosystems or economies) to simulate regional impacts of climate change. In the MINK (**M**issouri, **I**owa, **N**ebraska, and **K**ansas) study, the weather during the great drought of the 1930s was applied to the current ecosystems, economy, and population of four states (Rosenberg 1993). A study of the Mackenzie River basin in Canada used a recent period of warming and its observed impacts to simulate long-term impacts of global warming in the region (Cohen 1997). The Holdridge triangle of life zones has often been used to forecast place-specific changes in ecosystems based on anticipated changes in temperature and precipitation (Holdridge 1947, 1967; Emanuel *et al.* 1985; Pitelka 1997). Increasingly, efforts to assess impacts have begun to focus on regions smaller than the continental size areas of the Intergovernmental Panel on Climate Change Third Assessment. In the United States, the recently concluded National Assessment of Climate Change impacts began with 19 regions that were later aggregated into nine regions (including the scattered holdings of native Americans) and five activity sectors (National Assessment Synthesis Team 2000). In Canada, impacts were assessed for six regions and 12 sectors (Maxwell *et al.* 1997). There is a growing library of national impact studies around the world.

Responses

Although attention still focuses on the human responses required by such international agreements as the Framework Convention on Climate Change and the Kyoto Protocol, downscaling is evident in addressing responses, in this case making international agreement more difficult to attain. Blocs of nations (the so-called *umbrella group* led by the United States, the European Union, the G-7 group of developing countries, the small islands, and the oil producers) each advocate quite different response strategies, which has led to the collapse of talks to implement the Kyoto Protocol to reduce greenhouse gases worldwide by 5% below 1990 levels by 2010–12. Within countries, action plans are increasingly based on regions. In the United States, for example, some 19 regions (National Assessment Synthesis Team 2000) and 35 states have begun to formulate responses appropriate for their territories. In Canada, a study of adaptation considers six regions of the country (Maxwell *et al.* 1997). Such geographical downscaling is paralleled by sectoral downscaling. Climate impacts and adaptation in agriculture vary from place to place, and theoretically these impacts and adaptations are assessed along with other factors in the price of land. Using these differences, a set of studies have estimated impacts and adaptations for areas as small as counties in the United States (Mendelsohn *et al*. 1994, 1999; Polsky and Easterling 2000).

Upscaling bottom-up approaches

In recognition of the mismatches in scale among important domains of climate change, its consequences, and human responses, a growing interest in creating bottom-up approaches is evident. These have included local governmental, non-governmental, and corporate efforts, as well as the project that this volume summarizes.

Cities for climate protection

Local governments vary considerably both in their competence to undertake greenhouse gas reduction and in their willingness to do so (Collier and Löfstedt 1997). The most extensive current effort if this kind on the part of local governments is part of the international policy initiative entitled The Cities for Climate Protection Campaign, which has fostered an asphalt-roots movement (Chapter 12). The Cities for Climate Protection Campaign originated with the International Council for Local Environmental Initiatives Urban Carbon Dioxide Reduction Project, in which twelve North American and European cities worked together to develop and test methods whereby local governments could implement greenhouse gas emission reduction strategies (International Council for Local Environmental Initiatives 1996). Based on that project's results, the International Council for Local Environmental Initiatives established in 1995 the Cities for Climate Protection Campaign to bring together local governments committed to greenhouse gas emission reductions. By late 1999, the rapidly growing program had 403 members worldwide, including 68 in the United States. Together, these cities account for an estimated 8% of global carbon dioxide emissions.

Cities, counties, or metropolitan regions join the campaign by formally resolving to complete five key tasks: (1) an energy and emissions inventory; (2) a forecast of future emissions; (3) adoption of emissions reduction targets; (4) plans for local actions to achieve the reduction targets; and (5) implementation of those actions to reduce carbon dioxide and methane. To support such local government efforts, The Cities for Climate Protection Campaign has created analytical tools that allow municipalities to track their own emissions, forecast changes over time, and assess the potential impacts of diverse technical and policy measures designed to meet their target reductions.

Equally important, and perhaps of even greater importance in the long run, are corporate efforts to reduce greenhouse gases led by oil companies such as BPAmoco, Shell, and

Sunoco; energy companies such as Enron and American Electric Power; and such industrial giants as Boeing, Dupont, IBM, and Toyota. These private sector programs are facilitated by such groups as the Business Environmental Leadership Council of the Pew Center on Global Climate Change, and the World Business Council for Sustainable Development – World Resources Institute greenhouse gas protocol effort (http://www.ghgprotocol.org). Companies such as BPAmoco have adopted greenhouse gas emissions reduction targets of 10% below 1990 baseline emissions by 2010 and have created internal and external trading regimes to achieve these goals.

Non-governmental efforts are widespread, symbolized by the laborious effort to create a sandbagged dike across from the meeting hall at The Hague in The Netherlands at the crucial conference to implement the Kyoto Protocol, to remind delegates of the reality of global warming and sea-level rise. Non-governmental efforts are not restricted to national and international lobbying, but also create opportunities for individuals and their households to take steps to reduce their greenhouse gas emissions, partly by developing tools to calculate personal and household emissions.

Upscale and downscale approaches come closest together in the work emerging on the concept of vulnerability. These efforts seek to characterize vulnerability: the susceptibility to injury, damage, or harm of ecosystems, places, people, livelihoods, or activities. In vulnerability, three important factors come together: sensitivity to climate, exposure to climate change, and resilience or adaptive capacity (McCarthy *et al.* 2001). Unlike conventional downscaled methods of impact analysis that require some output from global climate models applied to a region or locale, vulnerability analyses can begin with the inherent characteristics of the place, group, or activity, and then assess its inherent sensitivity to climate and its capacity to cope with climate change or to respond to it. Even in the absence of a projected exposure, which is usually obtained from a downscaled model, it is possible to estimate the type and magnitude of exposure that would cause harm given inherent sensitivity and adaptive capacity, and to use these to suggest boundaries for climate change that would prevent excessive harm. Much more needs to be done in developing methods to characterize each of these elements at different scales, as well as to go beyond vulnerability to climate change to include vulnerability to the multiple environmental and social stresses that actually confront the places, peoples, and systems of interest (Clark *et al.* 2000). But this is where much of the frontier research will take us.

Global Change and Local Places

In this evolving context, *Global Change and Local Places* reports on a sustained and systematic effort to address the grand query of scale from a bottom-up perspective. The Global Change and Local Places project asked how, when, and where local knowledge, volition, and opportunity can be employed in addressing the great global challenge of human-induced climate change. The project began with the observation that scale domains differ for different parts of the global climate change causal chain. It postulates that understandings of the processes will differ according to the scale of observation, with greater variance, volatility, and value of local knowledge evident at local scales, and that downscaling and upscaling are likely to contribute different insights. And it postulates that scale interactions are significant in global change processes.

Global Change and Local Places does not answer the grand query; if such queries were easily answered, they would hardly be grand. The volume does provide an example of bottom-up research on global change in four quite different parts of the United States, an example that relates the near-universals of the greenhouse effect to the particulars of local emissions and efforts to mitigate them, and an effort that partly unravels the webs of structure and agency, and macro-processes and micro-behavior, that link the global and the local everywhere on Earth.

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